A Comparison of Two Different Approaches to Hydrazine Loading of Spacecraft: the use of SCAPE and Alternative Approaches

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ABSTRACT

The loading of spacecraft with Hydrazine type fuels has long been recognized as a hazardous operation. This has led to safety strategies that include the use of SCAPE protective suits for personnel. The use of SCAPE suits has an excellent safety record but has several drawbacks. Such drawbacks include the cost of maintaining and cleaning the suits, the health and training requirements of personnel, the reduction of mobility and dexterity of personnel wearing the suits, and the need to change personnel every two hours.

A study was undertaken to look at procedures and/or equipment to eliminate or reduce the time spent in SCAPE-type operations. The major conclusions have been drawn from observations of the loading of the JPL/NASA spacecraft Deep Space One (DS1) at KSC and the loading of a commercial communications satellite by Motorola at Vandenberg AF Base. Whereas the DSO operations made extensive use of SCAPE suits, the Motorola operations used only Splash suits with a two-man team on standby in SCAPE. The Motorola team used very different loading equipment and procedures based on an integrated approach involving the propellant supplier. Overall, the Motorola approach was very clean and much faster than the DS1 procedure. In addition, the Motorola Loading Cart is much simpler.

The DS1 spacecraft used a bladder in the propellant tank, whereas the Motorola spacecraft used a Propellant Management Device (PMD). The Motorola approach cannot be used for tanks with bladders. To overcome this problem, some new procedures and new equipment are proposed to enable tanks with bladders to be loaded without using SCAPE, using a modified Motorola approach. Overall, it appears feasible to adopt the non-SCAPE approach while maintaining a very high degree of safety and reliability.

INTRODUCTION

Due to the hazardous properties of Hydrazine loading operations, the operators that conduct the fueling process are required to don Self-Contained Atmospheric Pressurized Environment (SCAPE) attire. Operators who don SCAPE attire must meet special requirements and there are definite limitations to SCAPE attire.

1. Personnel must pass rigorous medical tests to qualify to use SCAPE attire.
2. Personnel are required to attend specialized training.
3. An operator may be in SCAPE attire for a maximum of two hours, and then must rest for two hours before donning the SCAPE attire again.
4. Working in SCAPE attire is difficult and bulky. Extra time is required to accomplish even simple tasks.
5. SCAPE attire can be used only a limited number of hours and must then be refurbished. At KSC there are over a hundred suits and the maintenance costs are considerable.

NASA has assigned JPL the task of studying various approaches to reducing the number of hours operators have to spend in SCAPE attire. A reduction in the time spent in SCAPE attire may be accomplished by modifying the Hydrazine loading procedure, thereby reducing the operator's overall exposure to Hydrazine. A reduced exposure could allow for the use of the less restrictive SPLASH attire, which would permit the operators to work more efficiently thus speeding up the overall time required to carry out hazardous operations.

Disclaimer. The research described in this paper was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

With the use of SPLASH attire, it becomes increasingly important to have a sensitive Hydrazine detector with a fast response. If a small spill is detected, a standby crew, in SCAPE attire could move in quickly and take over to contain and clean up the spill. The search for a fast response Hydrazine detector at the 10 ppb level is described in Ref. 1.

APPROACH

Alternative Hydrazine loading process were identified and reviewed to determine their ability to

- Remove operators from the hazardous site as much as possible. To reduce or eliminate operations conducted in SCAPE attire.
- Adapt to the existing overall system without requiring major modifications
- Be less hazardous than the current system, both in terms of system safety as well as personal safety
- Outweigh advantages (less hazardous, faster, etc.) over disadvantages, such as initial capital cost, etc.

Three approaches were investigated.

1) The use of robotics
2) The use of a different, highly automated Loading System
3) New approaches used in industry

In the first approach, the JPL Hazmat Robot (Hazbot) performed simulated tasks. It was found that the Hazbot, without a special holding tool, is unable to disconnect A/N fittings (Ref. 2). A Hazbot is also unable to apply the necessary delicate soft metal seal to valve fittings. Additionally, there were concerns regarding the potential hazard of a powerful robot in the presence of S/C.

In the second approach, the use of the Martin-Marietta Hydrazine Automated Loading System (Ref. 3) was evaluated. This system has been tested successfully, however, with simulant propellants only. The system was not put into use. It is presumed that this system has not been used in actual operations due to its complexity and high cost and its limited flexibility in terms of its mobility and ability to service S/C with different designs and fuel valve configurations.

The third approach involved investigating a new fueling system developed by Motorola. In this process, SCAPE attire has been eliminated except for standby use. The Motorola Fueling System works well for propellant tanks without bladders. Because most JPL S/C have Fuel Tanks with bladders, this system would require modifications. A new design of the loading equipment has been proposed to overcome these problems.

CURRENT JPL HYDRAZINE FUEL TRANSFER PROCESS

The Hydrazine fuel transfer process begins with the transfer of Hydrazine from a KSC Facility Hydrazine transport tank to JPL's Propellant Service Cart's fuel tank. This transfer process is conducted in a secluded and controlled area (Fuel Handling Facility) to minimize risks to personnel and Spacecraft (S/C). After the Service Cart Tank has been filled, it is transported to the highbay where the S/C resides. A detailed instruction manual is followed which describes the specific fuel transfer process for each individual S/C. A specific and continuously measured amount of fuel is transferred from the Service Cart into the S/C Fuel Tank utilizing the Hydrazine Fuel Transfer Process.

Due to the hazardous nature of the Hydrazine Fuel Transfer Process, SCAPE attire is required for all portions of the operation except the Preparation Process. A Hazard Analysis revealed that the highest hazard potentials occurred during the Sampling Process and during the Flexline disconnect of the Hydrazine Fuel Transfer Process.

Hydrazine Fuel Transfer Process

Figure 1 shows a simplified flowchart of the 60 page Hydrazine Fuel transfer process. Figure 2 shows the major connections between the Service Cart and the S/C. A two-person crew plus a standby person from safety complete the following tasks:

Preparation :

The Service Cart's Fuel Tank is connected to the S/C Tank by means of Flexlines (Fig.2). (The connecting fittings are A/N fittings).

- To fill the S/C Tank with liquid fuel, one line of the Service Cart is connected to the liquid (bottom) side of the S/C Tank (below the bladder).
- To fill the S/C tank with the pressurant gas, another line is connected to the vapor (top) side of the S/C Tank.

The Flexlines are then leak tested to insure a leak-free connection.

1. The main valves on the S/C Tank are opened to connect the Flexlines with the interior of the S/C Tank.
2. The S/C Tank and the Flexlines are evacuated through the vacuum connection to remove all air.
3. The S/C valves are closed.

Propellant Transfer :

4. Helium pressure is added (see Figure 2) to the top of the Cart Tank by opening Valve E of the Helium Tank and Valve A of the Cart Tank. By opening Valve B of the Service Cart, the propellant then flows from the Cart Tank up to Valve D of the S/C Tank, thus filling the Flexline with propellant.
5. The S/C Service Valve D is opened and the Helium pressure, above the liquid Hydrazine in the Cart Tank, pushes the liquid into the S/C Tank.
6. The flow of Hydrazine is continuously controlled during the filling process.
7. When the S/C Tank has the right amount of fuel, as shown by the scale on the Service Cart, the propellant Service Valve is closed and torqued .

(During the above operations, the pressure drop across the bladder diaphragm is kept below a maximum value by adjusting or venting the Helium pressure above the diaphragm.)

Propellant Sampling :

8. Samples of Hydrazine are withdrawn from the Service Cart via an open jet of fuel directed into an open glass sample bottle. These samples are then analyzed to determine the composition (to detect impurities and decomposition products) before the S/C is launched.

This sampling process is conducted with open containers, and is therefore considered a high hazard operation.

Vacuum Aspiration of Lines:

9. The Flexlines are cleaned via evacuation. A liquid Nitrogen trap removes Hydrazine vapors before they can enter the vacuum pump. (See Figure 2).
10. The propellant Flexline is disconnected from the S/C Service Valve. When the A/N fitting of the connection is loosened, external air is drawn into the fitting and the line; sweeping away liquid Hydrazine droplets into the liquid Nitrogen trap.

There is sometimes a small "puff" of Hydrazine vapor when the fitting is disconnected. There may be liquid Hydrazine caught in the screw threads. The process of disconnecting the Flexline from the S/C Service Valve is a high hazard step.

Leak Test of Service Valve:

11. A leak test of the S/C Service Valve is conducted.

Pressurization of Tank:

12. The S/C Tank is pressurized with Helium on the gas side of the diaphragm in the tank (see Figure 2).
13. The Gas Service Valve of the S/C is closed and torqued.

Clean-up :

14. The Flexlines are disconnected from the S/C and the Service Cart and flushed with water. The resulting wastewater is put into a drum for waste disposal.

FUELING OPERATION OF DEEP SPACE ONE (DS1) AT KSC

The Hydrazine fueling operation for Deep Space One (DS1) conducted at the Kennedy Space Center (KSC) was viewed remotely on monitors and photographically documented. The procedure is described in detail in Reference 4. Figure 3 shows the high-bay fueling area. The DS1 S/C is in the left foreground, and is connected with Flexlines to the Service Cart in the center. The drums on the right hand side are for disposal of hazardous waste. Figure 4 shows the withdrawal of a Hydrazine sample from the Service Cart after completion of the transfer. Several sample bottles must be filled. An open liquid jet of fuel enters the bottle that is held by the operator. The haze above the liquid Hydrazine is clearly visible, indicating a high concentration of Hydrazine, either in vapor, haze or droplet form. When filling the sample bottles, the flow of Hydrazine is not restricted between bottles, consequently Hydrazine liquid is spilled over the bottles (and on the operator's gloves) as one bottle is withdrawn and the other bottle is placed under the jet. A bucket is placed under the bottles to try and catch the spilled Hydrazine. Figure 5 shows the capped Service Valves for liquid and gas on the S/C after all operations are completed.

THE MOTOROLA FUELING SYSTEM

Hydrazine is the fuel required for the attitude control system of the IRIDIUM satellites. The simultaneous Hydrazine fueling of five IRIDIUM satellites on one S/C was recently conducted at Vandenberg Air Force Base, using a new fueling system developed by Motorola in cooperation with Olin, the supplier of Hydrazine. The following figure and process descriptions of the operation are provided based upon my observations. The process is described in a recent patent (Ref. 4). Neither Motorola nor Olin would provide any additional written description of the system.

Figure Descriptions

Figure 6 shows a simplified propellant transfer schematic of the Motorola Fueling System. The required amount of fuel is provided in a special transportation drum (Fuel Tank) by the fuel supplier, Olin, and then transported by conventional means to the site. The Fuel Tank has 3 built-in valves, shown schematically as Valves F, G, and H on top of the Fuel Tank. There is also a plugged fuel transfer Flexline packaged on top of the drum. There are two ports in the drum, one is a liquid standpipe to the bottom of the drum, and the other is a gas port. Olin also provides a second drum, which is evacuated (Vacuum Tank). The Motorola Cart has two Helium vapor supply pressure regulators. The Helium gas cylinder is not mounted on the Motorola Cart. All the valves on the Motorola Cart (not shown for simplicity) are both manual and automatic for remote control operation.

Figure 7 shows the S/C with the 5 satellites and the five fuel drums placed around it. The remote control room and the Motorola Cart in front of it can also be seen.
Figure 8 shows the Fuel Tank with the Flexline coming from the top valve area, as well as the JPL investigators.
Figure 9 shows the inside of the Remote Control Room. The Motorola Cart with the three pressure gages, and the S/C that holds the 5 IRIDIUM Satellites can be seen on the other side of the window.
Figure 10 shows the operators in SPLASH attire (without Air Supply)

Process Description (see Figure 6)

- ***SPLASH attire is required for this operation, because operations are conducted where the team is only "one Valve away" from Hydrazine vapor.***
- Note: Valves, A, B, C, F, G, and H must be operated manually, thus requiring the presence of the Hydrazine Loading Team in the Highbay.
- Crewmembers are in the Control Room at all times when liquid Hydrazine flows through the Flexline. A two men crew in SCAPE attire is on standby in an adjacent room during the loading process in case of emergency.

1. All lines are purged with Helium.
2. All lines are Leak Tested.
3. Personnel move to the windowed Control Room for observations and to conduct the remote portions of the filling process.
4. Helium under pressure is introduced through Valves D, E, and F into the upper half of the Fuel Tank. Liquid Hydrazine is subsequently transported from the bottom of the Fuel Tank, up the standpipe, and through Valves H, J, and K, into the S/C Tank. When the last of the Hydrazine liquid is transferred from the bottom well into the S/C Tank, the rate of pressurization of the S/C Tank changes. The completion of this liquid Hydrazine transfer is indicated on a monitor in the Control Room. The Motorola System delivers the required amount of fuel to the S/C Tank to within plus or minus one pound. Note: There is a small cavity or well at the bottom of the standpipe that assists in emptying the tank.
5. Valves F and H are then closed while Valve G is opened. This allows the Helium flow to bypass the Fuel Tank to the S/C Tank until the required pressure is reached. Note: Gaseous Helium sweeps out any Hydrazine remaining in the Flexline to the S/C Tank, thus cleaning the line.
6. Valve K is then closed. At this time the crew is one valve away (Valve K) from Hydrazine vapor (liquid Hydrazine is on the bottom of the tank and Hydrazine vapors are on top).
7. Valve G is closed and Valve H is opened. This connects the high pressure Flexline to the lower pressure Fuel Tank, resulting in a gas flow from the Flexline into the Fuel Tank. Residual liquid droplets of Hydrazine in the Flexline are then swept back into the Fuel Tank.
8. Valves H, F and D are closed, and Valves G and E opened, thus allowing the Flexline access to the Vacuum Tank. By opening Valve C, the Helium in the Flexline, and any Hydrazine vapors are pulled into the Vacuum Tank.
9. The Flexline is disconnected from the S/C Tank as follows:
   - Ball Valve, J is closed and the A/N fitting connecting the Flexline to the Service Valve K is loosened but not disconnected. This causes air to flow into the evacuated Flexline.
   - Valve J is cracked open a couple of times, allowing air to purge the Flexline again into the Vacuum Tank.
   - With Valve J closed, the A/N fitting is disconnected and a plug is put on the end of the Flexline (between the J and K Valves); sealing it off from the atmosphere.
   - A seal is put on the Service Valve K outlet.
   - A tertiary seal is put over the Service Valve K structure in the form of a cover cap with an O-ring seal.

   There are now 3 seals between the liquid Hydrazine in the S/C Tank and the atmosphere.
10. The Flexlines are capped and packed on top of the Fuel Tank and the Vacuum Tank for return to Olin, where the cleaning of the tanks and the lines will take place.

Monitoring of Hydrazine was conducted during the operation with both portable and facility instruments sensitive to 10-ppb. No detectable Hydrazine was found.

Advantages to the Motorola Fueling System

1. Active operations are conducted in SPLASH attire. SCAPE attire is used for emergency standby purposes only.
2. Propellant quantity measurements are not required at the launch site.
3. Propellant sampling (both pre- and post- transfer) is not required at the launch site.
4. Hazardous vapor scrubbers are not required.
5. Liquid Nitrogen traps are not required.
6. The Motorola Cart is simple and only holds the Helium Gas supply and controls. The Cart Fuel Tank has been eliminated.
7. Propellant is not wasted because the propellant supplier provides the required amount.
8. There is virtually no opportunity for the atmosphere to be contaminated.
9. There is no need to transfer the propellant from the transportation tank to the Cart Fuel Tank. The Cart Fuel Tank is no longer necessary.
10. The task of cleaning the Flexlines and the tanks has been transferred to the propellant supplier, who is better equipped to do this.
11. Hydrazine analysis can be transferred to the supplier if desired.
12. Contaminated pressurant gas is caught in the Vacuum Tank and is disposed of by the supplier of the fuel.
13. Because the Motorola Fueling System is considerably faster (3-4 hours) when compared to the JPL Fueling System (12- 14 hours), the time required for the facility to be on alert, and for unnecessary personnel to evacuate the building can be reduced.

Disadvantages to the Motorola Fueling System

1. An automated Service Cart that can be operated remotely is needed.
2. The quantity of propellant required must be determined in advance.
3. The operator must be willing to let Olin take the Hydrazine samples and possibly perform the analysis.
4. The supplier must certify and maintain the Fuel Tank, Valves and associated Flexlines.
5. The Motorola Fueling System, as described, only works for S/C Fuel Tanks equipped with a Propellant Management Device (PMD), i.e. without a bladder.

   Currently PMDs are not required on all S/C. Perhaps, this could be a requirement for future propulsion systems. As an alternative, new technology is proposed below which modifies the Motorola System for S/C Tanks that have bladders.

PROPOSED MODIFICATIONS FOR S/C TANKS WITH BLADDERS

There are many advantages to the Motorola Fueling System over the JPL Fueling System for S/C with Fuel Tanks equipped with PMDs as described above. However, the Motorola Fueling System cannot be used as described for S/C that have Fuel Tanks with bladders. Two modifications to the existing Motorola Fueling System have been developed which would solve the following concerns in regards to filling S/C Fuel Tanks with bladders.

1) Helium gas must be prevented from entering the propellant side of the S/C Fuel Tank; and
2) The Flexline must be purged with Helium to blow liquid Hydrazine back into the Fuel Supply Tank.

Proposed Motorola Fueling System-"Add-On"

An "Add-On" System to the Motorola Fueling System has been designed to accommodate S/C Tanks with bladders. Figure 11 shows the Motorola System, modified by the "Add-On" System. The "Add-On" System consists of two new items added to the Flexline configuration. The first item is the combination of a Liquid/Gas Detector (P) and an automated Valve Q. Between the Fuel Tank and the S/C Service Valve, K, the Liquid/Gas Detector, P is installed. The Liquid/Gas Detector indicates whether the Flexline holds liquid Hydrazine or pressurant gas. The Liquid/Gas Detector may utilize electrical capacity, optical density, flotation, or another appropriate sensor. When liquid Hydrazine is transferred from the Fuel Tank to the S/C Tank, at the point where the Fuel Tank is empty, Helium will travel up the standpipe through the Flexline to Point P. When the Liquid/Gas Detector senses Helium gas at Point P, a signal is generated that closes an automated Valve Q upstream. There is now liquid in the line from Point P into the lower half of the S/C Tank.

The Service Valve, K must then be closed. This operation must be conducted in SCAPE attire because there is liquid Hydrazine under pressure behind the Service Valve K. (The crew is only one valve away from <u>liquid</u> Hydrazine).
The Liquid/Gas Detector, P is then turned off, which automatically opens Valve Q. Helium is supplied through Valve S and a new Purge Fitting. (See Figure 12). The Helium then pushes the liquid Hydrazine in the Flexline back into the Fuel Tank.
Figure 12 is a schematic design of the Purge Fitting which consists of an elbow which connects to the Flexline and to the Service Valve, K. This Purge Fitting has a Helium supply tube which allows the Helium gas to purge liquid Hydrazine from

the dead space in front of Service Valve K back into the Flexline and the Fuel Tank. The remaining clean up of the contaminated Helium gas in the Flexline may be conducted in a similar manner as described in the original Motorola method.

In summary, by using a modified Flexline that incorporates a Liquid/Gas Detector, an automated valve, and a Purge Fitting, the Motorola system can be used for S/C Tanks with bladders. This modified Motorola Fueling System can be carried out in SPLASH attire except when closing the S/C Service Valve. This portion must be conducted in SCAPE attire and should only take approximately 30 minutes.

CONCLUSIONS

Motorola Fueling System

1. SCAPE attire requirements are eliminated when using the Motorola Fueling System during Hydrazine Loading of S/C, which have a Propellant Management Device. Only SPLASH suits are used in the active operations because the operator is only exposed to vapor Hydrazine behind the Service Valve, as opposed to liquid Hydrazine. SCAPE attire is used in a standby mode only, in the event of an emergency.

2. At least a dozen S/C have been fueled in this manner. The operation is fast and safe. The most hazardous operation was identified as the disconnection of the propellant line from the S/C propellant service valve, however there were no detectable levels of Hydrazine as determined by an electrochemical, portable instrument with a 10-ppb sensitivity.

3. A unique feature of the system is that the propellant Flexline is used for the pressurant gas, which leaves the Flexline free of any Hydrazine.

4. The transportation tank for the Hydrazine, supplied by Olin, becomes part of the transfer system. Another transportation drum is used as a waste collection system.

5. The Motorola Fueling System has several other main advantages, including:

- There is no need for liquid Nitrogen traps.
- There is no need for a vapor scrubber.
- The supplier, at their facility, performs Clean up of the Flexlines and tanks. The sampling of the Hydrazine is also conducted at their facility.

Modified Motorola Fueling System

6. The Motorola Fueling System can be modified to fuel S/C Tanks with bladders. An "Add-On" System to the Motorola Fueling System has been designed as a result of this S/C Fueling System Review which enables a Modified Motorola Fueling System to be used when fueling S/C Tanks with bladders.

   The "Add-On" System consists of a propellant Flexline with a Liquid/Gas Detector, a special Shut-off Valve, and a Helium Purge Fitting.

7. Fueling S/C Tanks with bladders utilizing the Modified Motorola Fueling System would require primarily SPLASH attire. SCAPE attire would only be required when disconnecting the propellant feed line from the liquid service valve, because there is only one valve between the operator and pressurized liquid Hydrazine. This disconnection operation takes only a few minutes, therefore the time spent in SCAPE attire would be greatly reduced.

JPL's Propellant Service Cart

The current JPL procedure to collect Hydrazine samples from the Service Cart after the transfer is completed results in the considerable spillage of liquid Hydrazine on the gloves of the operator and into an open bucket within the highbay. This process can be modified to keep the Hydrazine contained during sampling.

RECOMMENDATIONS

1. Review the Motorola Fueling System procedures with NASA, and particularly with KSC to determine whether this system should be adopted within NASA for S/C with Propellant Management Devices.

2. Review the newly designed "Add-On" System to the Motorola Fueling System with NASA, and particularly with KSC to determine its' merits for fueling S/C tanks with bladders.

3. Carry out a cost /benefit analysis for the Motorola Fueling System and the Modified Motorola Fueling System if from a technological and safety point of view, they are found to be satisfactory.

4. Conduct a pilot operation with simulated propellants to determine the practical aspects of the proposed Modified Motorola Fueling System for S/C tanks with bladders.

5. Modify the current liquid Hydrazine sampling equipment and procedures (used with the JPL Propellant Service Cart) to fully contain Hydrazine.

REFERENCES

1. JPL Internal Document D-16320, "Hydrazine Detection System", 20 October 1998, by Pamela R. Brown and John Houseman.

2. JPL Internal Document D-16374, Progress Report on "Safe Universal Hydrazine Loading Cart", 10 Nov. 1998, by Pamela R. Brown, John Houseman, Julie Jackson and Ruth LeBlanc.

3. Functional Requirements Document, Titan Centaur, TC 424-1, "Hydrazine Automated Loading System", 3 Nov. 1992, Martin-Marietta Corporation, Denver.

4. JPL Internal Document: Procedure DS1 133, Deep Space One, Flight System: RCS Propulsion Subsystem, "Propellant Fill and Pressurization", by D. R. Quarles, June 23, 1998.

4. U.S. Patent 5,582,366, "Satellite Fueling System and Method Therefor", issued December 10, 1996, to Hamant, McBride and Cubbage, and assigned to Motorola, Inc.

FIGURES

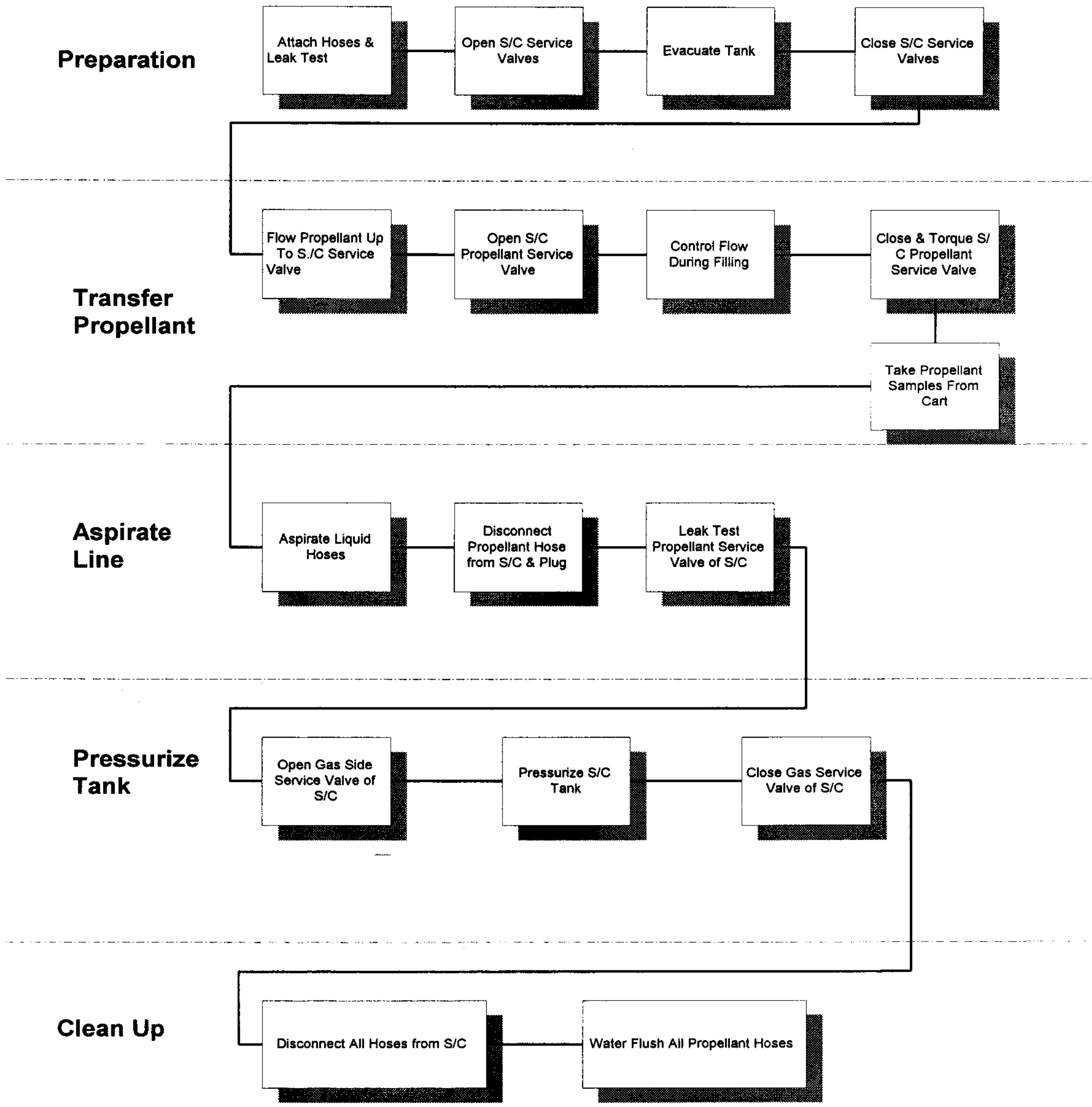

Fig. 1 Propellant Loading Flowchart

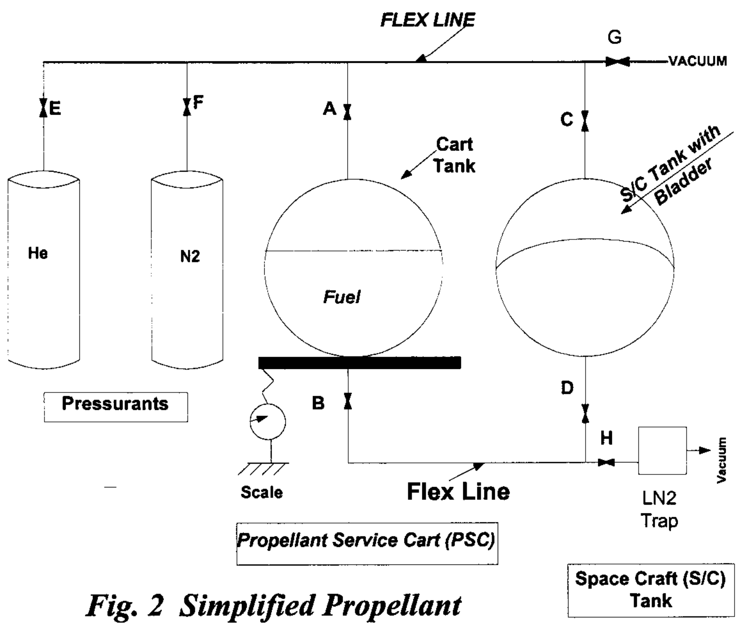

Fig. 2 Simplified Propellant Transfer Schematic

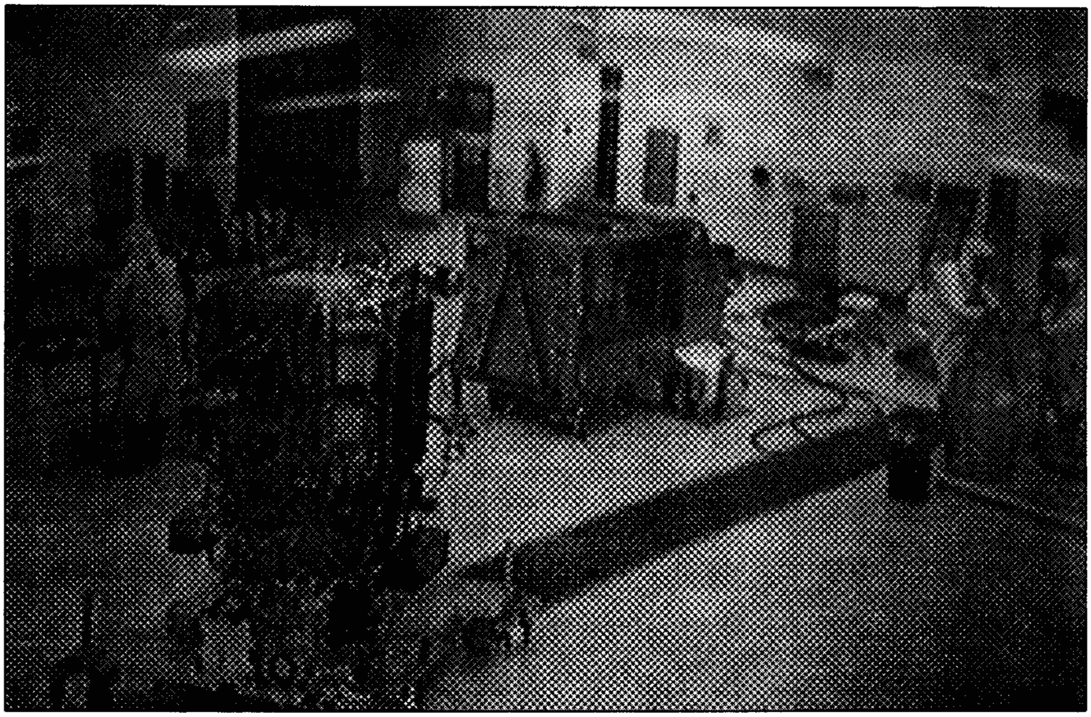

Fig. 3 Highbay Fueling Area

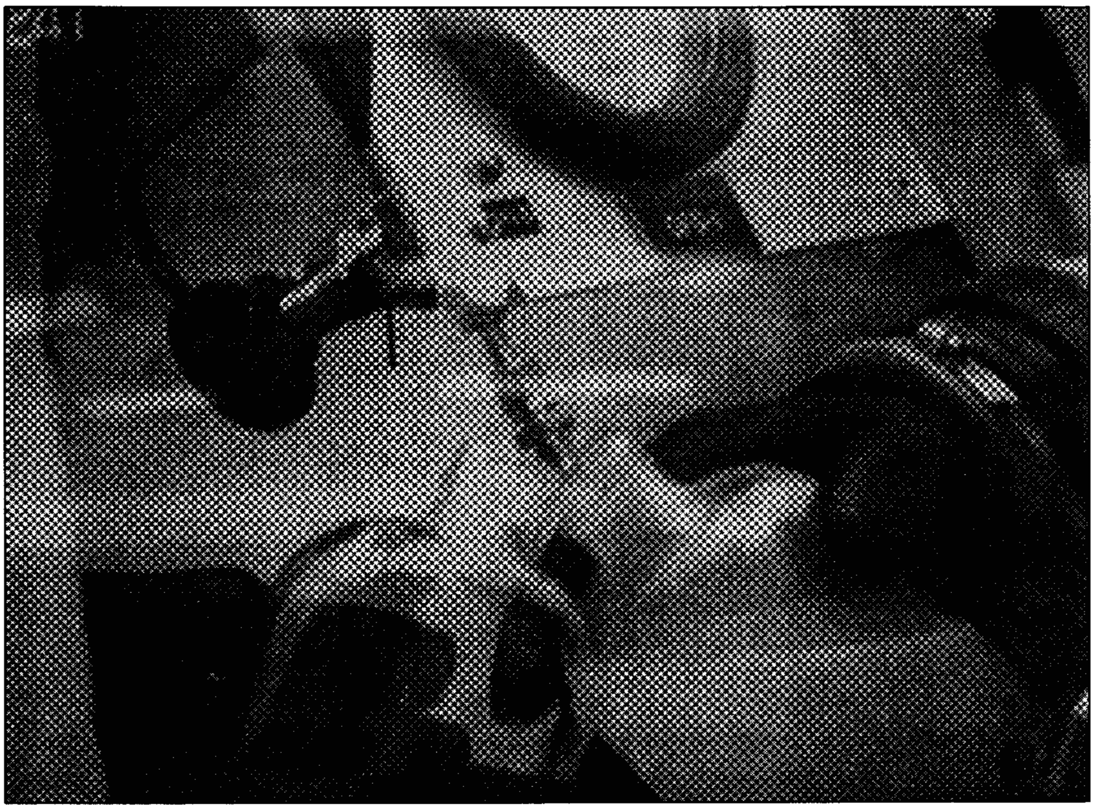

Fig. 4 Sampling of Hydrazine from Cart

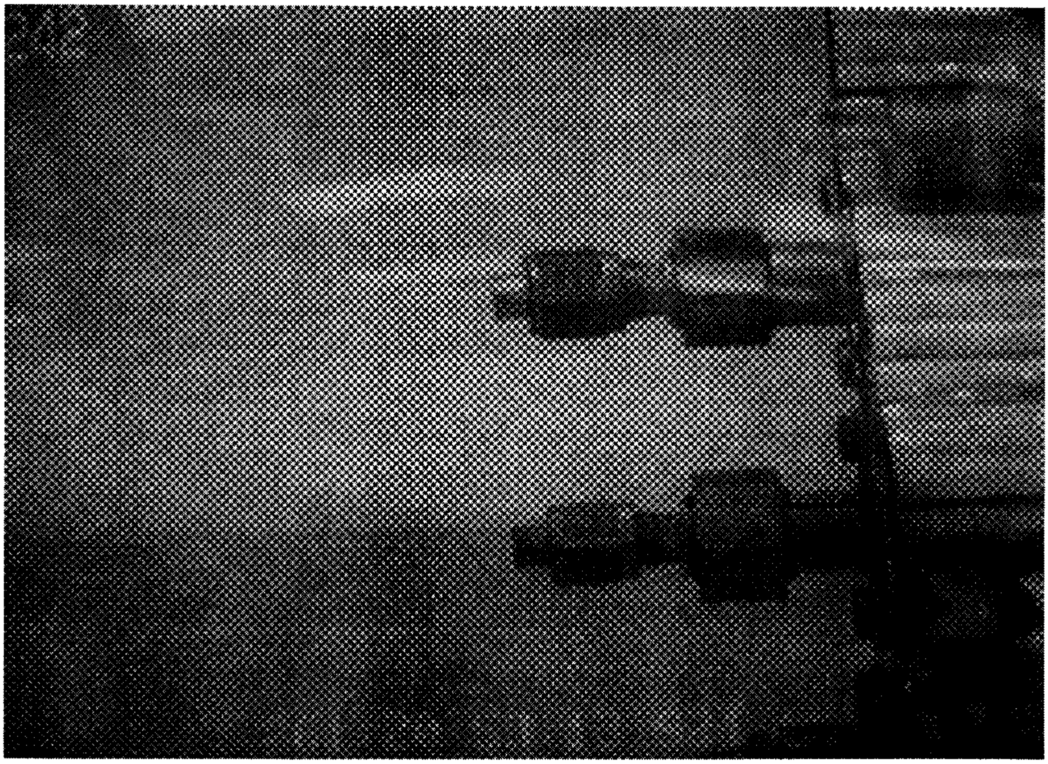

Fig. 5 Capped Service Valves

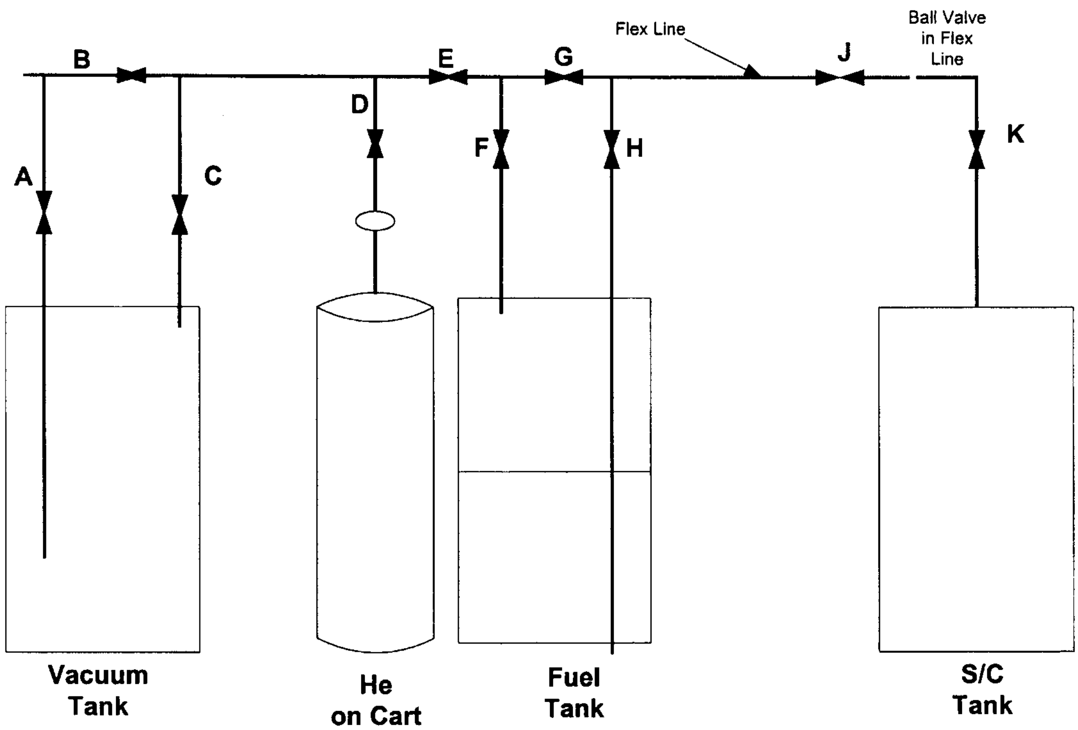

Fig. 6 Simplified Motorola System

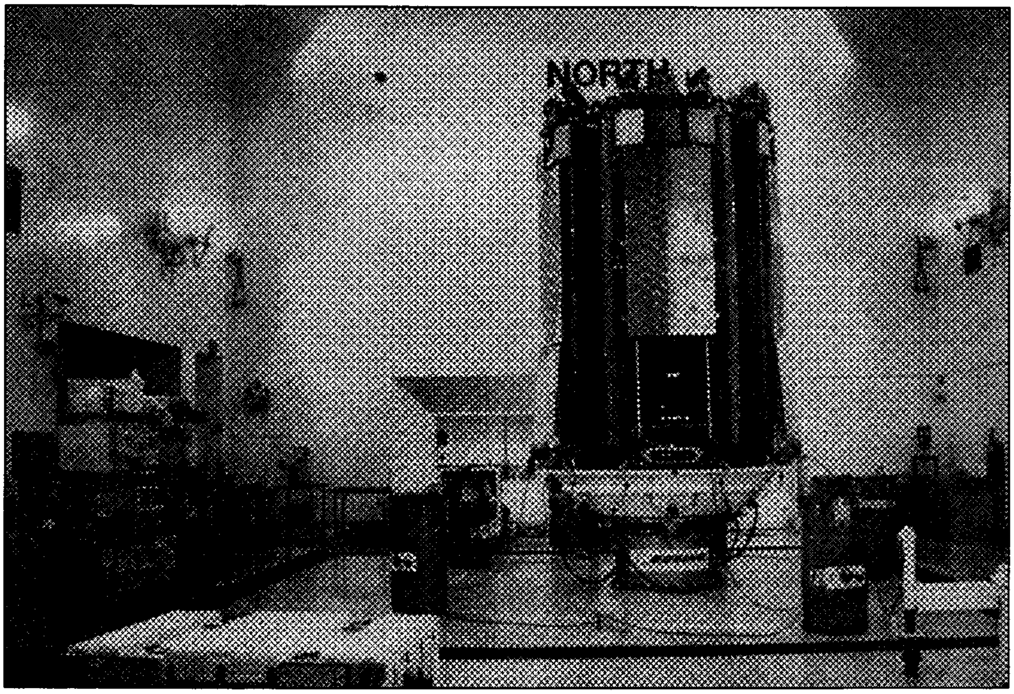

Fig. 7 Spacecraft with Five Satellites and Five Fuel Drums

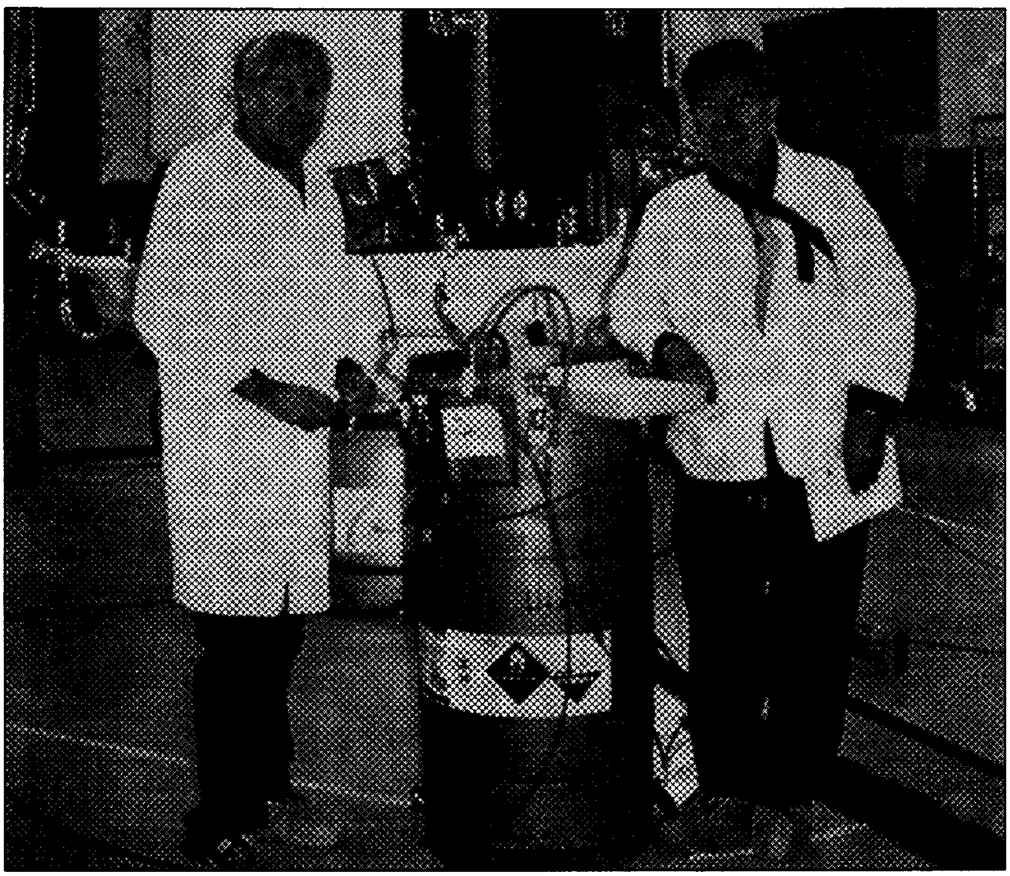

Fig. 8 Olin Special Fuel Tank

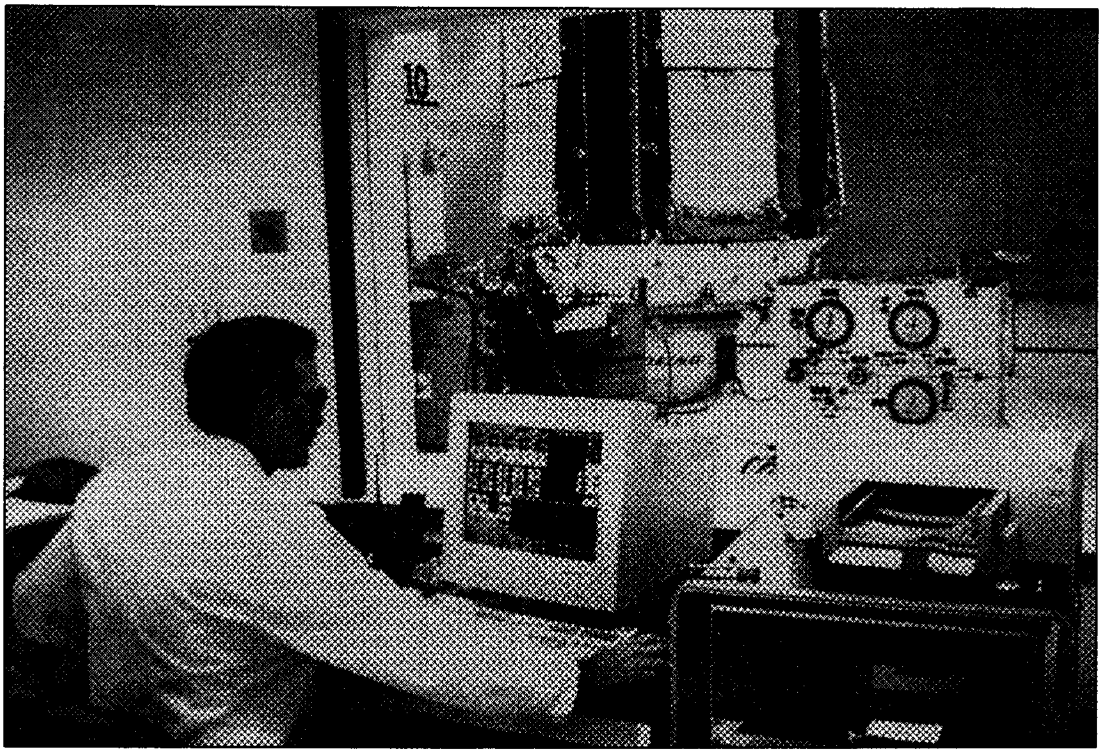

Figure 9. Remote Control Room

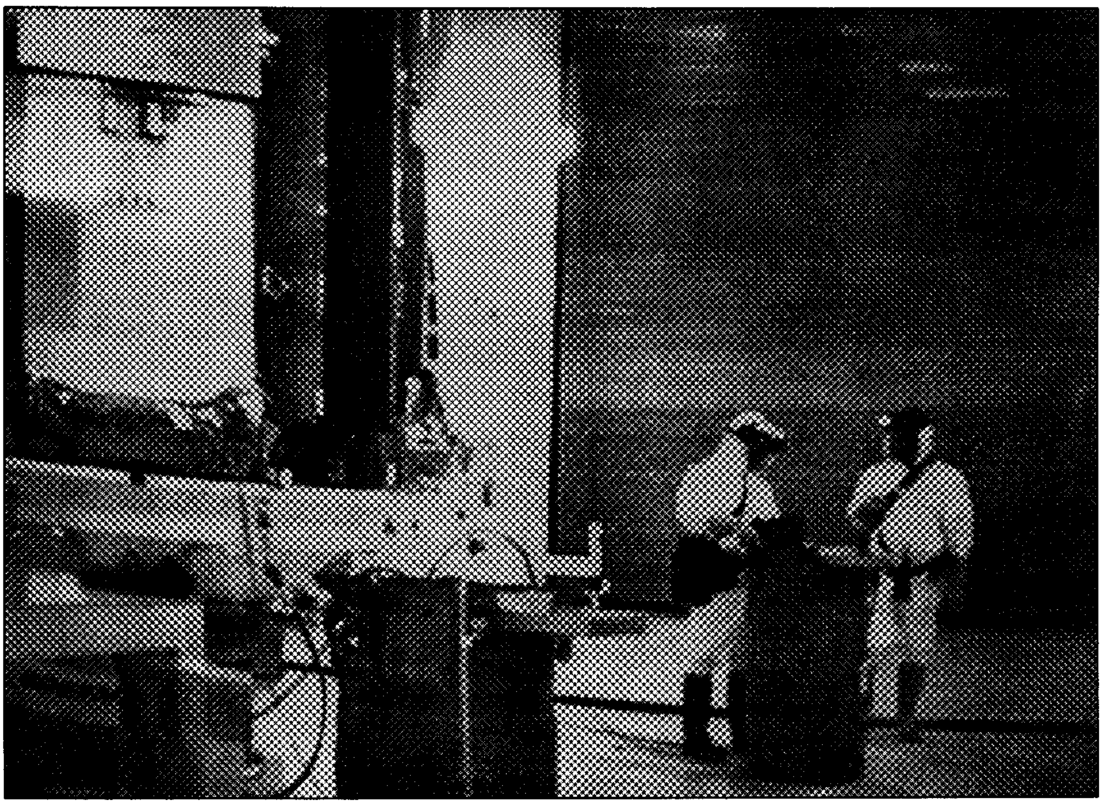

Fig. 10 Operators in SPLASH

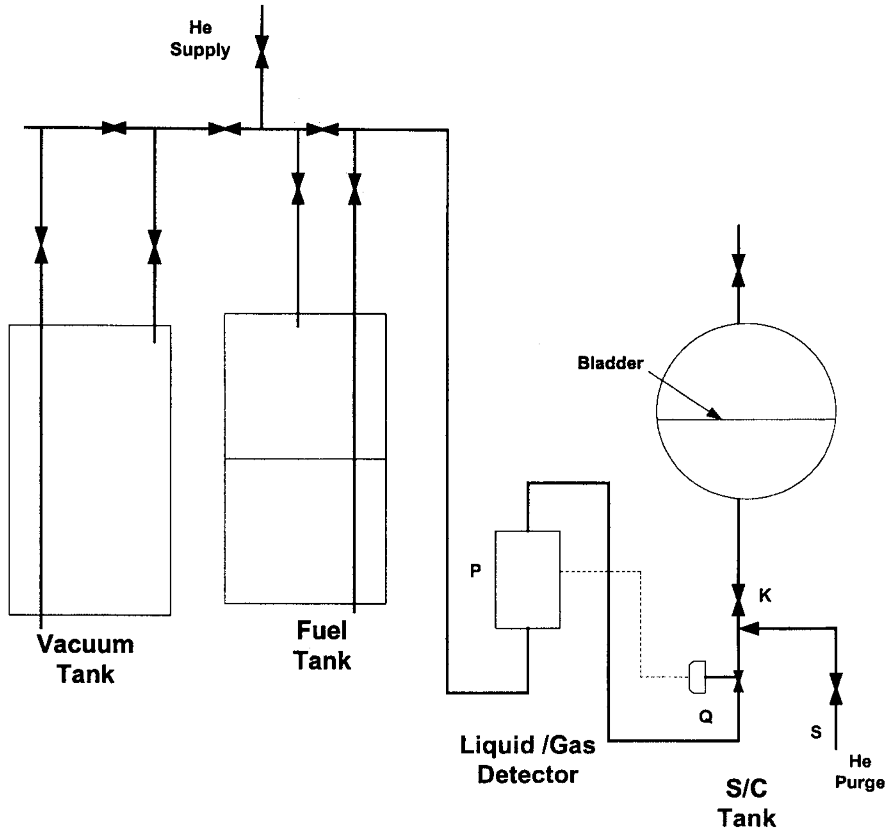

Fig. 11. Proposed Add-on for Tanks with Bladders

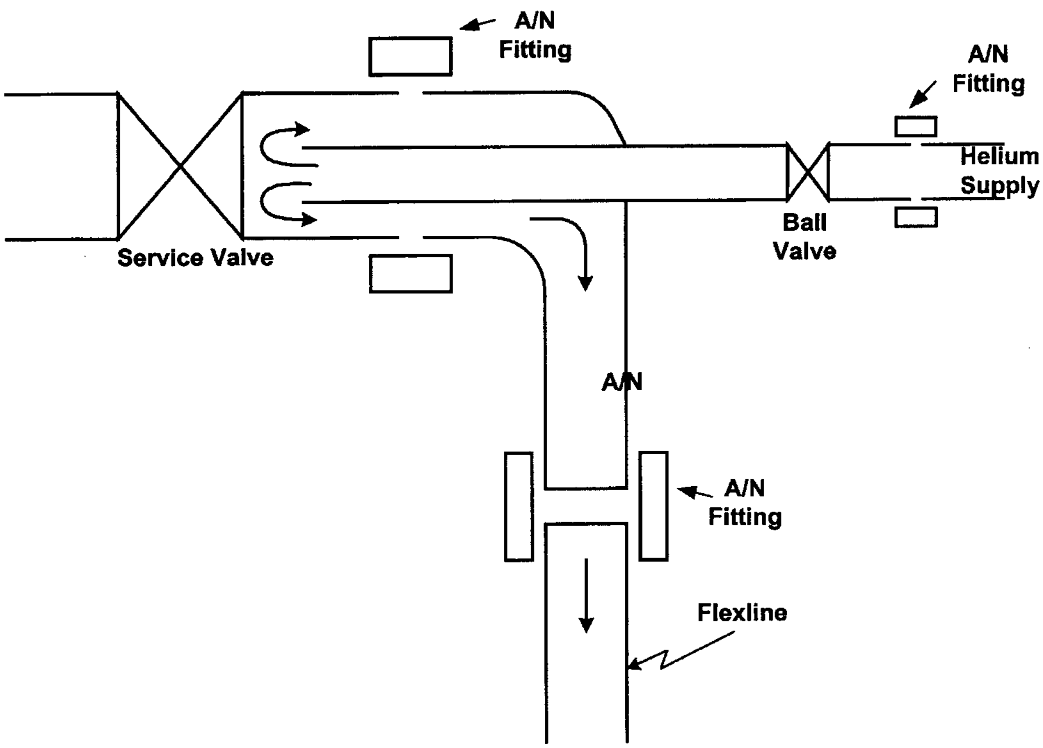

Fig. 12 Purge Fitting between Service Valve and Flexline